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The road to Ultra High-Energy Cosmic Radiation observation from space

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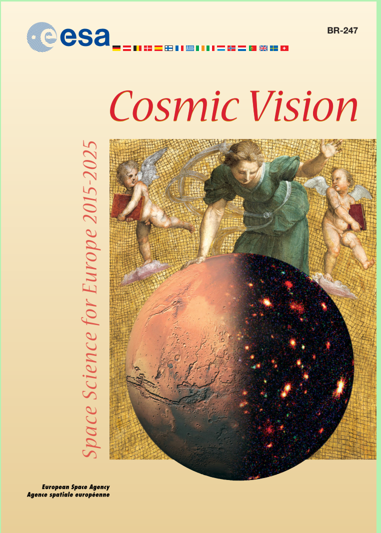


The objective and observational approach

Objective

Observation of Ultra High Energy Cosmic Rays (UHECR): $E \gtrsim$ some$\cdot 10^{19}$ eV.

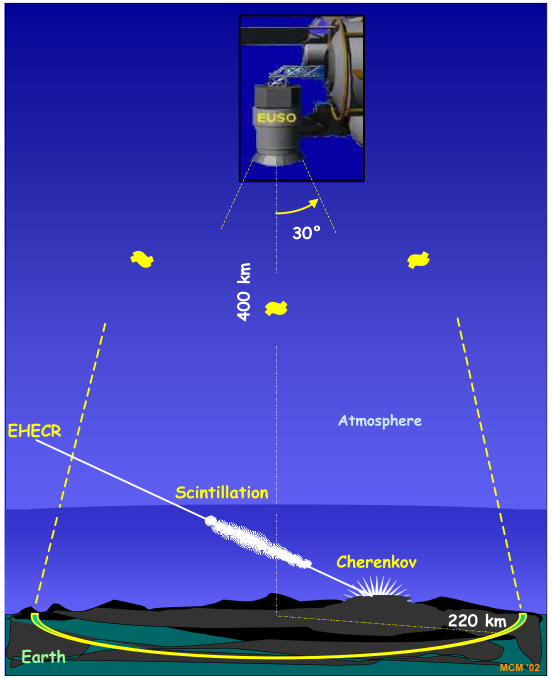
Experimental approach (John Linsley, 1981)

- Observation, by means of a space-borne experiment, of the Extensive Air Showers, (EAS) produced by the interaction of a primary UHECR with the atmosphere, by looking down to the Earth from Space (*AirWatch* concept).
- An EAS can be detected by observing the atmospheric fluorescence light, isotropically produced all along the EAS development (technically: luminescence/scintillation).
- The observation of the forward beamed Cherenkov light diffusely reflected by the Earth can help the EAS reconstruction.

$\Longrightarrow$ The atmosphere as a calorimeter (passive, changing, outside human control).

In orbit around the Earth to collect more events: key points

- Large distance (≈ 400 km), large FoV ($\gamma \simeq 30°$); plus an expected duty cycle $\approx (0.10 \div 0.20)$:
  $\Longrightarrow$ Large Effective geometrical aperture $\mathcal{A}_{\rm GEO}^{\rm eff} \approx (0.6 \div 1.2) \cdot 10^5\ {\rm km}^2 \cdot {\rm sr}$.
  Observe a large mass of atmosphere ($\approx 10^{12}$ tons).
- The fluorescence light is isotropic and proportional, at any point, to the number of charged particles in the EAS: record the EAS development.
- The identification of EAS from weakly interacting primary particles starting the EAS deep in the atmosphere is possible.
- All sky coverage is possible with one observatory.
- Approach complementary to the observation from the Earth surface: different energy ranges (partially overlapping), different systematic effects.



The Observation of UHE Cosmic Radiation

- Observation from Space aims to extend the statistics at the highest energies with respect to ground-based experiments, the Pierre Auger Observatory (PAO) in particular.
- It is likely that the next generation of experiments for the observation of UHECR will be space-based $\Longrightarrow$ exploit the larger instantaneous geometrical aperture with respect to ground based experiments.
- The realistic framework for a next-generation mission is ESA Cosmic Vision: the time-frame for the operation of the experiments starts just after 2015.
  The conception, optimisation, design and construction of the apparatus has to start a long before
  In fact ESA is expected to issue a Call for Mission Proposals by the end of 2006.
- Before the start of any detailed design for a new mission the results from the PAO will be studied to tune the design of the new apparatus accordingly.

Which physics of UHECR after PAO ?

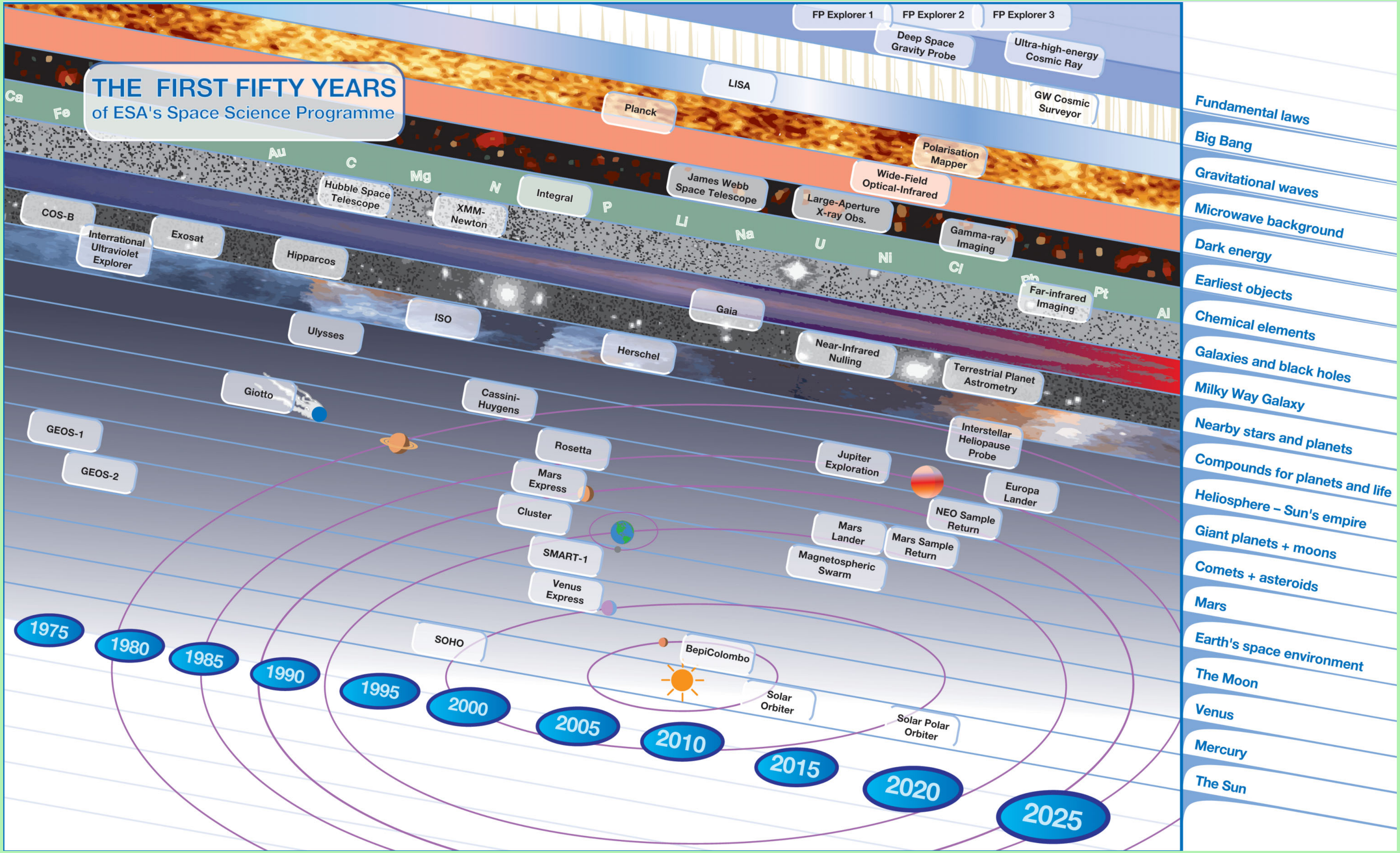
Whatever the scientific results from the PAO will be,
a further generation of experiments, with larger instantaneous geometrical aperture,
might provide additional important scientific results,
with totally independent measurements with respect to the PAO ones,
thanks to the increased statistics, including:

- determination of the shape of the energy spectrum above the GZK energy;
- detailed study of the shape of the GZK feature, providing information on the source distribution and particle injection spectrum;
- astronomical identification of sources;
- improved composition studies;
- the instantaneous aperture two orders of magnitude larger than typical ground-based experiments might open the observation of burst-like phenomena and weakly interacting particles.

It is, at least, a top-class AstroPhysical problem.

The ESA Cosmic Vision program 2015-2025

- Next-generation space-based observation of UHECR is supported by the PAO Collaboration and by APPEC.
- Moreover the European Space Agency recently released its road-map for 2015-2025: (ESA Cosmic Vision program), which includes a space mission for the observation of UHECR.
- An ESA Call for Missions for the period 2015-2018 is expected by mid-2006: the time schedule for proposal is dictated by ESA.
- You need to be ready if you want any chance of entering the game: a launch in $\approx$ 2015 requires a phase-A well before 2010.
- The new time-scale will allow to carry on a number of preparatory activities and experiments which will be useful/necessary to optimise the experiment design.


THE FIRST FIFTY YEARS
of ESA's Space Science Programme
FP Explorer 1
FP Explorer 2
FP Explorer 3
Deep Space Gravity Probe
Ultra-high-energy Cosmic Ray
LISA
GW Cosmic Surveyor
Planck
Polarisation Mapper
James Webb Space Telescope
Wide-Field Optical-Infrared
Large-Aperture X-ray Obs.
Gamma-ray Imaging
Hubble Space Telescope
XMM-Newton
Integral
Far-infrared Imaging
COS-B
International Ultraviolet Explorer
Exosat
Hipparcos
Gaia
ISO
Ulysses
Herschel
Near-Infrared Nulling
Terrestrial Planet Astrometry
Giotto
Cassini-Huygens
Interstellar Heliopause Probe
GEOS-1
Rosetta
Jupiter Exploration
GEOS-2
Mars Express
Europa Lander
Cluster
NEO Sample Return
Mars Lander
Mars Sample Return
SMART-1
Magnetospheric Swarm
Venus Express
SOHO
BepiColombo
Solar Orbiter
Solar Polar Orbiter
Ca
Fe
Au
C
Mg
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1975
1980
1985
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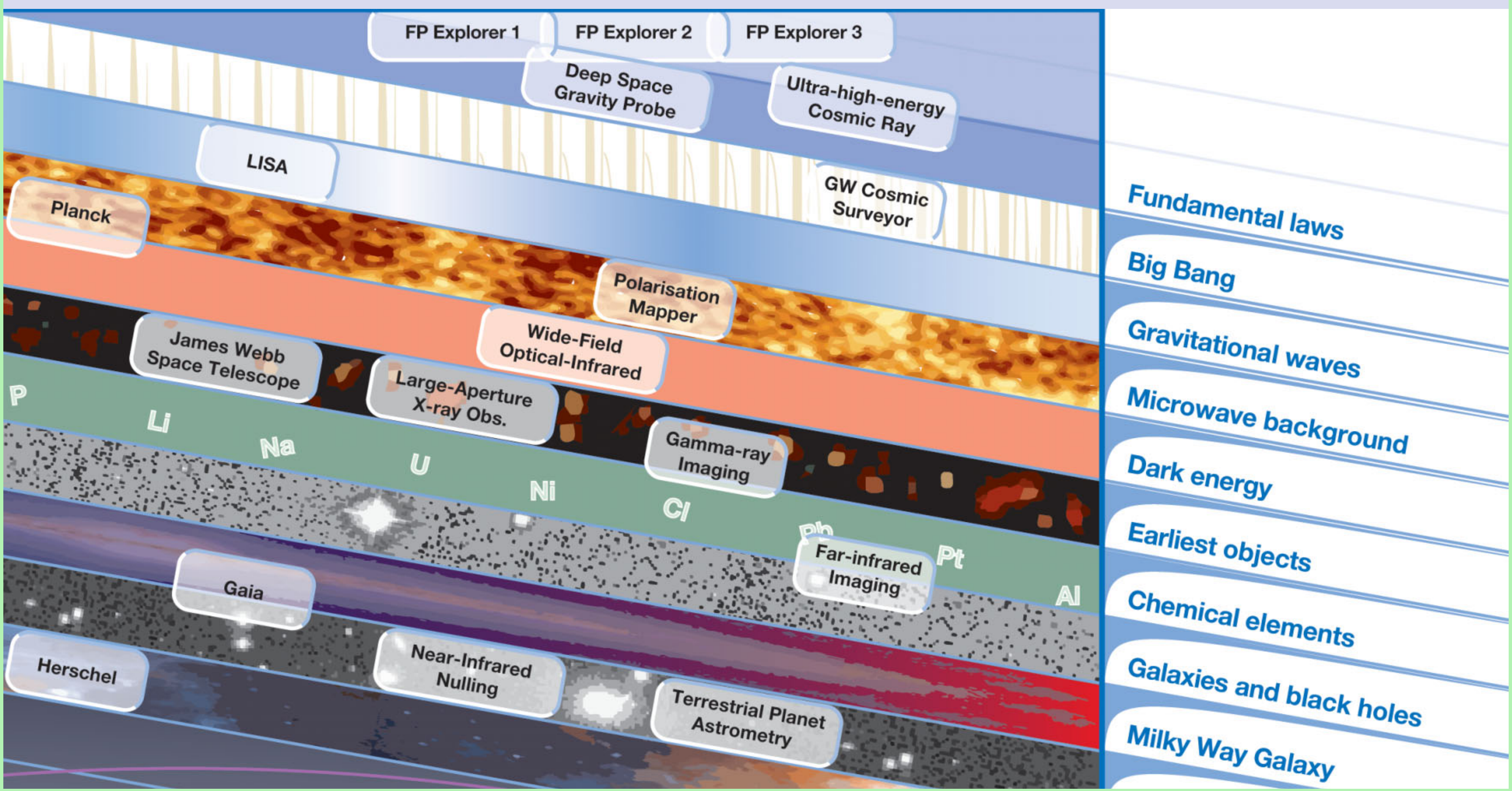
1995
2000
2005
2010
2015
2020
2025
Fundamental laws
Big Bang
Gravitational waves
Microwave background
Dark energy
Earliest objects
Chemical elements
Galaxies and black holes
Milky Way Galaxy
Nearby stars and planets
Compounds for planets and life
Heliosphere – Sun's empire
Giant planets + moons
Comets + asteroids
Mars
Earth's space environment
The Moon
Venus
Mercury
The Sun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Big Bang
Gravitational waves
Microwave background
Dark energy
Earliest objects
Chemical elements
Galaxies and black holes
Milky Way Galaxy

EUSO went on-hold: how to go on?

A road-map must be defined such that:

- the scientific objectives must be carefully defined, based on the results of PAO;
- the mission-for-Everything is most likely impossible (too large dynamic range in energy) one will be forced to select the scientific objectives ...;
- the scientific objectives must be converted in requirements for the experimental apparatus and the required R&D must be defined as well as the mission profile (orbit, ...);
- as a function of the latter points, the intermediate steps required to achieve a mission for UHECR from space shall be defined: theoretical studies, simulations, technological models, preliminary experiments (path-finders), ancillary measurements,... ;
- it is going to be a (very) long way.....

How to prepare the Mission

Preparation of the Mission for ESA CV 2015-2025

In order to prepare the Mission one needs:

- a serious R&D program;
- a number of technological developments and tests;
- a number of intermediate steps.

Intermediate steps

Intermediate steps might include:

- balloon flights to test/measure some low-energy CR;
- technological tests via stratospheric airplane flights;
- support activities, including: fluorescence yield and Cherenkov albedo measurements;
- one (or a few?) small missions on either a micro-satellite or a nano-satellite;
- ...

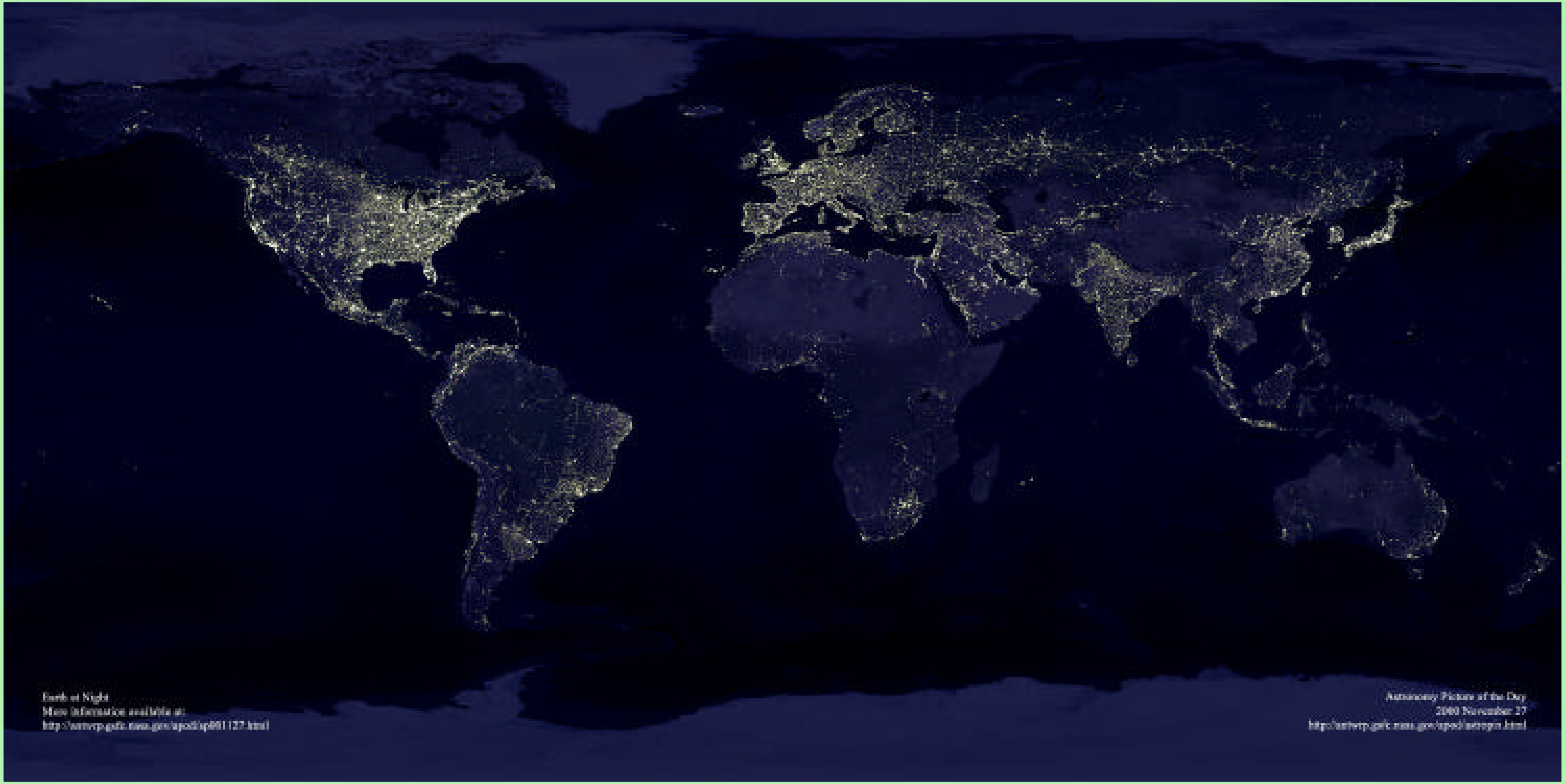
A path-finder micro-satellite (xyz-pathfinder)

- A pioneer/path-finder to characterise the background and do functional and technological tests on a micro-satellite is a fundamental step to prepare such a mission.:
  A low-cost micro-satellite (a few MEuro) doing near-UV remote sensing from space.
- A small mission to:
  - measure/characterise the background from space;
  - perform functional tests on critical parts of the apparatus;
  - qualify the observational approach;
  - test some technological items;
  - if two satellites are available: development and test of binocular observation.
- Some possible useful fall-back include:
  - Remote Sensing
  - Planetary Environments
- The time-scale requires this mission to be considered for ≈ 2010:
  this kind of mission is strictly interconnected with the progress of the ESA CV mission (if any...).

The background to UHECR observation from Space

- UHECR observation from Space will be operated ($300\ \mathrm{nm} \lesssim \lambda \lesssim 400\ \mathrm{nm}$) looking at nadir during night-time from an altitude of $\approx (300 \div 600)\ \mathrm{km}$.
- The entire sources of background around the Earth must be considered. High inclination orbit: scan of the Earth surface at large, avoid equatorial regions....
- The luminosity of the sources has to be studied and their variability in space and time coordinates as well.
- The nadir viewing implies that specific conditions of the earth atmosphere within the field of view must be considered.
- The upward light transport in atmosphere is dominated, in clear sky, by molecular scattering. The earth atmosphere albedo will be modified in presence of clouds and/or aerosols.

The background at night: night-glow, $\oplus$ ...



The background to UHECR observation from Space

- Data exist from space: a future dedicated experiment must demonstrate its specificity.
- A mix of measurements and guess-estimates allows the following random background to be quoted, within large uncertainties:

$$B \approx (3 \div 9) \cdot 10^{11} \text{ photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}.$$

  in the $300 \text{ nm} \lesssim \lambda \lesssim 400 \text{ nm}$ wavelength range.

- The presence of clouds increases the level by a factor: ≈ 1.5.
- Recent measurements by the MSU satellite *Tatiana* confirm these values.
- For a typical (ESA Cosmic Vision) large mission this implies a background rate:

$$b \approx 5 \text{ MHz/pixel !!!}$$

  with a comparable signal rate at the maximum of a $E \approx 10^{19}$ eV.

- Background subtraction is mandatory !
  $\Longrightarrow$ Background fluctuations are important and one must know them !

The background to UHECR observation from Space

- Try to get the fastest photometric measurements of all kind of expected UV backgrounds:
  - almost continuous background (air-glow,...);
  - transient luminous events (lightnings, elves, sprites,...);
  - man-made sources (cities,...).
- Not only an integrated spectrum but look for very fast events, down to the μs time-scale.
- Link to other applications through atmospheric physics.
- Use a system with a large dynamics of detection, even if limited to a single UV band: statistics and time profile can be obtained with a small apparatus.

The background to UHECR observation from Space

Main background sources

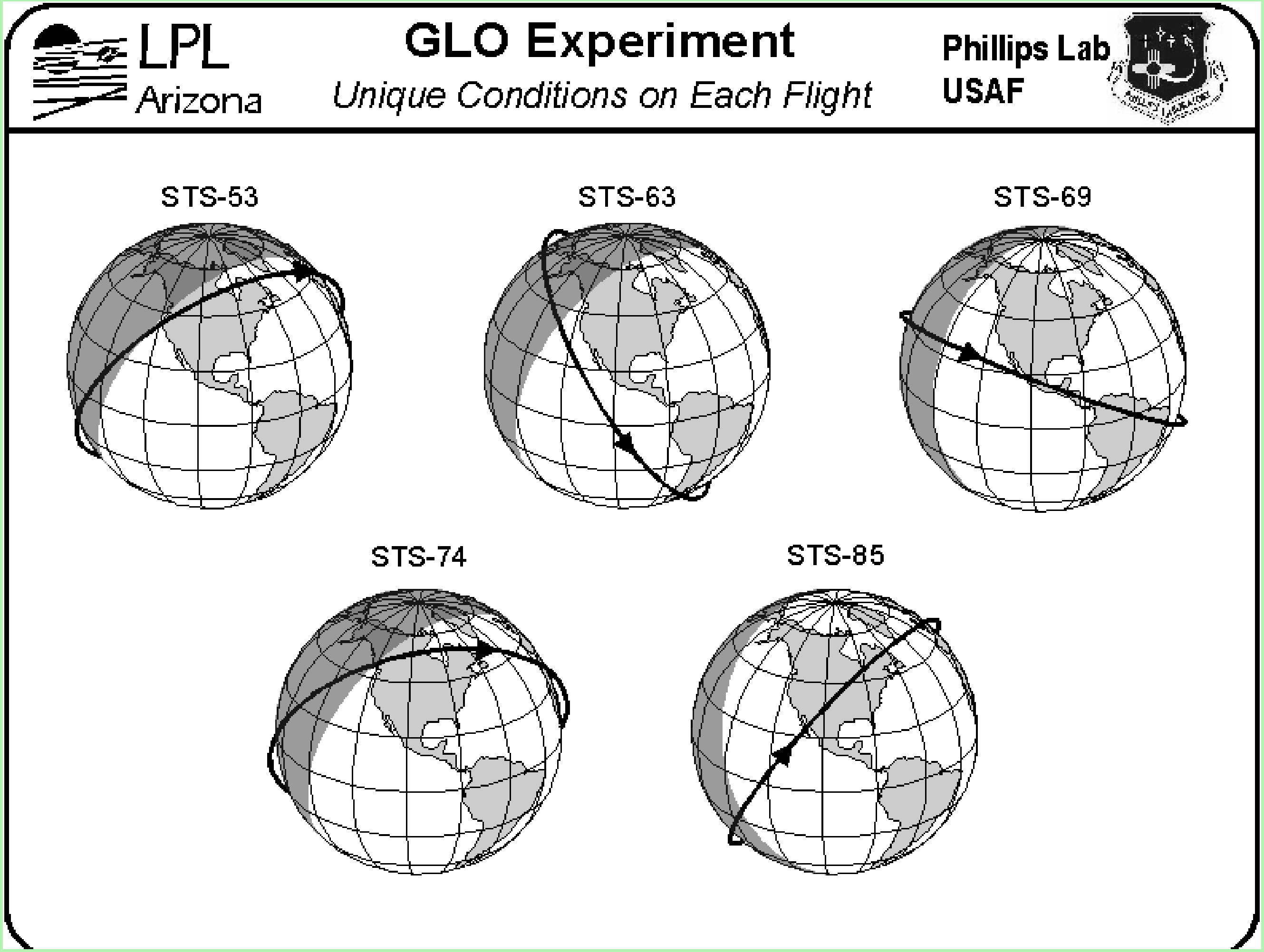
The many sources of background can be roughly divided in three broad categories:

- natural night sky diffuse and slowly varying sources;
- man made sources, like city lights;
- transient luminous phenomena in lower and upper atmosphere.

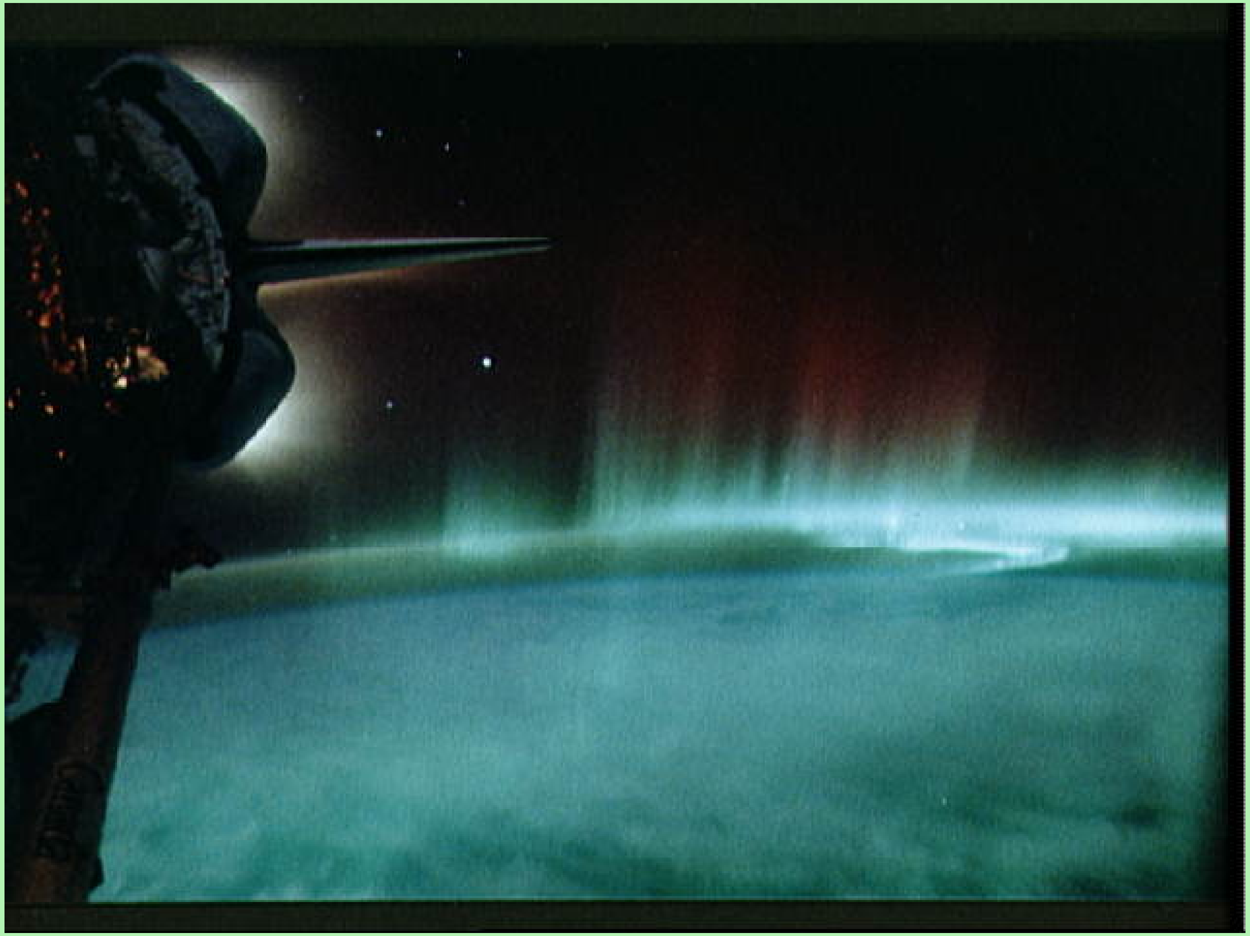
Other sources

- satellites and debris in the sun light,
- meteors,
- airplanes,
- low-energy Cosmic Rays,
- *satellite glow*,
- ...

GLO: the Arizona Air-glow Experiment

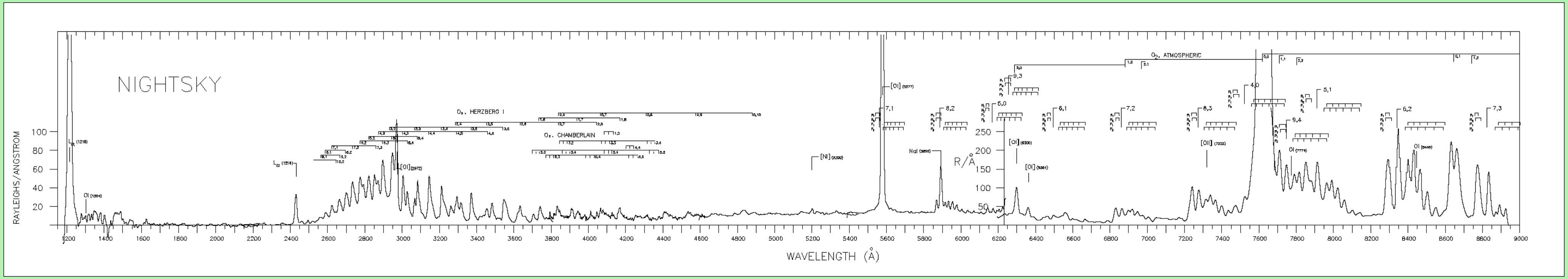


GLO: the Arizona Air-glow Experiment



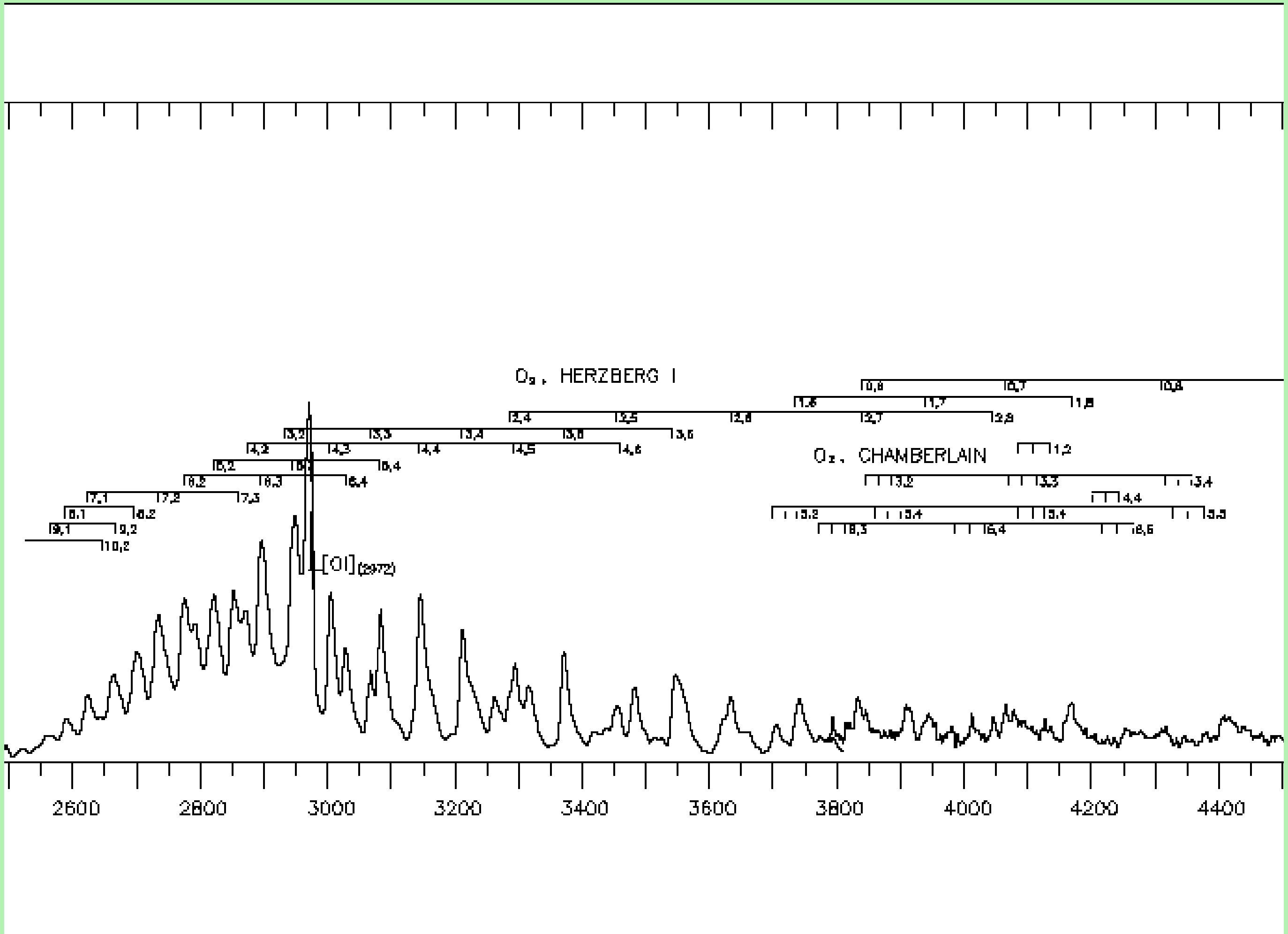
- Beware of satellite induced glow...!

GLO: the Arizona Air-glow Experiment

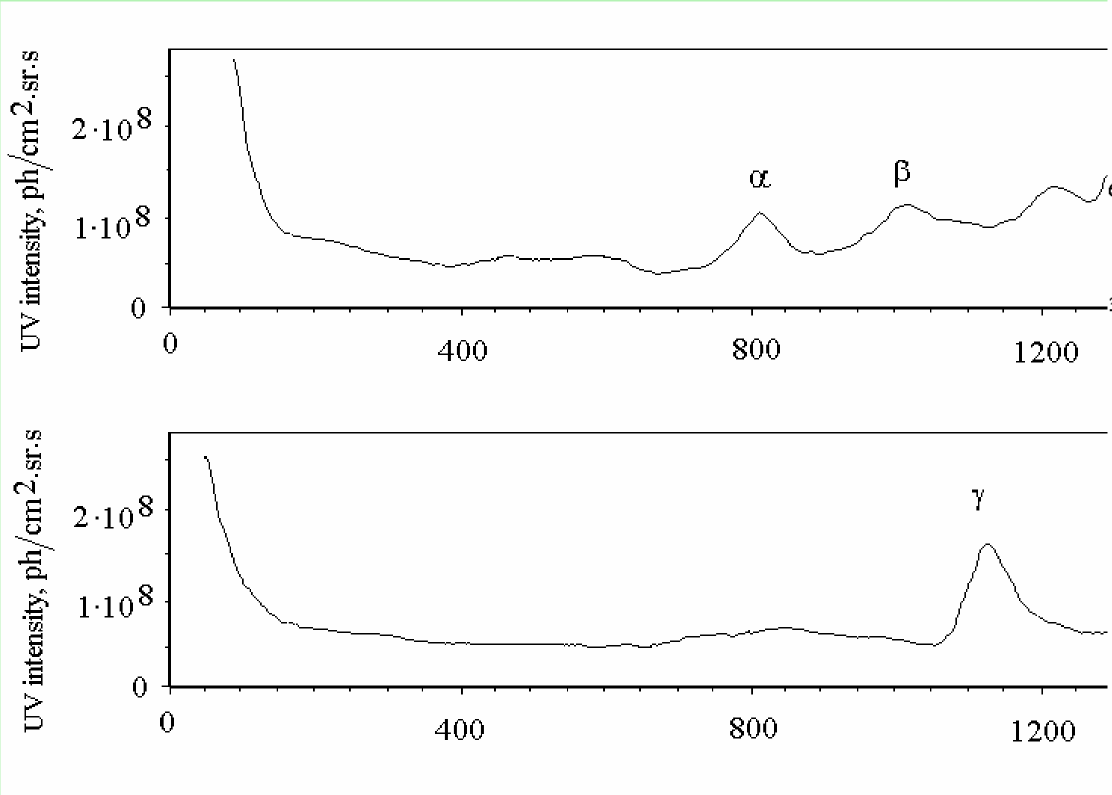


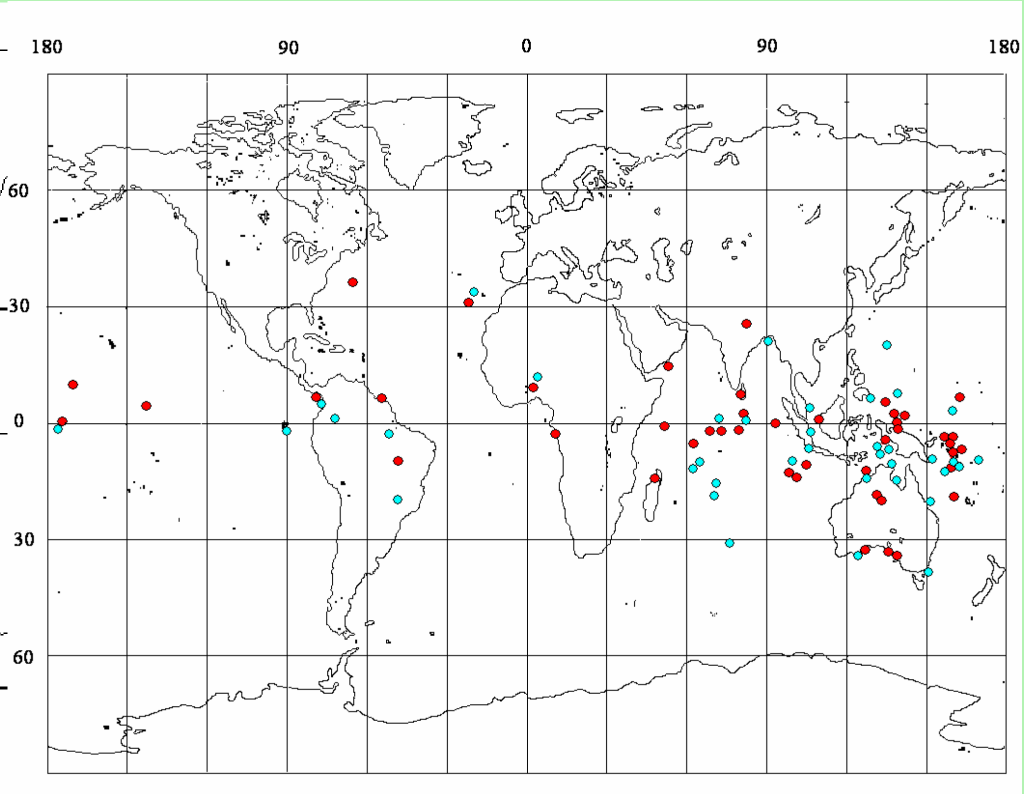
Detailed measurement of the spectrum.

GLO: the Arizona Air-glow Experiment



TATIANA: the MSU education experiment





- The results are consistent with known results but
- beware of the observed light flashes...!

A possible xyz-pathfinder mission

To characterise the background in the wavelength range $300 \text{ nm} \lesssim \lambda \lesssim 400 \text{ nm}$ for use with the next-generation of experiments for UHECR observation from Space.

Very Preliminary (tentative) Requirements

- Look for space-time variability of the sources
  at the level required for UHE Cosmic Radiation from space:
  $$\Delta\ell \approx \text{ km at the Earth surface and } \Delta t \approx (0.01 \div 0.1) \text{ ms},$$
  the space and time scales of a typical EAS.
- No self-triggering (external trigger: random, pre-defined, externally triggered, *on pass*......).
- Limited on board storage.
- Capability to take data above specific Earth locations
  (targeted study, ground-based EAS simulator,...)
- A few different wavelength channels?
  The three main wavelengths for air scintillation plus the full $300 \text{ nm} \lesssim \lambda \lesssim 400 \text{ nm}$?

A possible implementation (just a back-of-the-envelope exercise)

- In orbit at $H \approx 400$ km (suitably chosen), inclination $i \simeq 50°$ (elliptic orbit for changing the observed target at the Earth?).
- Optics Field Of View: $\gamma \simeq 3°$ (half-angle).
- Optics aperture: $D \simeq 0.5$ m, with optical throughput $\varepsilon \gtrsim 0.5$.
- Focal Length: $f \simeq 1.0$ m ($f/\# \approx 2$, easy design).
- Focal Surface diameter: $D_{FS} \simeq 0.1$ m.
- Focal Surface made of (possibly different types of sensors):
  - either ≈ 16 R7600/R8900 Hamamatsu MAPMT (1024 channels);
  - or a matrix of SiPM (or any other new sensor).
- Band-pass filters on different locations on the FS.
- Estimated rate on the Photo-Detector: $B_O \approx 20$ MHz (overall). $B_O \approx 20$ kHz (per pixel).
- Counting time limited by the satellite speed: ≈ 7 km/s: $\Delta t_{\mathtt{MAX}} \approx 0.01$ s and $\langle n \rangle \approx 2 \cdot 10^2$ /pixel.

Design, Operation and Expected Outcome

- Many degrees of freedom in the design will require careful optimisation: it depends on our requirements and available resources.
- Calibration by observation of known sources at the Earth, after measuring the Atmospheric transmission.
- Other uses of such a instrument might be possible: for instance atmospheric phenomena in the upper atmosphere might be observed (Sprites, Blue Jets and Elves).

Preliminary estimate of the budgets

- Size: $\approx (0.5 \times 1.2)$ m.
- Mass: ≈ 50 kg (rough estimate from the *EUSO* experience).
- Power: ≈ 2 W (rough estimate from the *EUSO* experience).
- Telemetry: TBD.

Conclusions

- The precise knowledge of the expected background is essential to the UHECR mission design.
- A small path-finder is an essential intermediate step for the UHECR mission design.
- It must be a part of the road-map to the UHECR-from-Space mission,
  as it looks like a pure ancillary measurement,
  unless interesting atmospheric physics can be found....
- In order to be useful it has to be done in a relatively short times-scale (before 2010).
- Its outcome will impact on the future of the UHECR mission.
- But it is a large effort, even if it is for a small Mission:
  a solid Collaboration must be built...